Language Primitives and Type Discipline for Structured Communication-Based Programming

— Subject Reduction and Type Safety Theorems —

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Abstract

Session primitives and types provide a flexible programming style for structural interaction, and are used to statically check the safe and consistent composition of protocols in communication-centric distributed software. Unfortunately authors working on session types have recently realised that some of the previously published systems fail to satisfy the basic theorems of Subject Reduction and Type Safety. This report discusses the issues involved in higher-order session communication, presents a formulation of the recursive types as well as proofs of the Subject Reduction and Type Safety Theorems of the original session typing system by Honda-Vasconcelos-Kubo in ESOP'98. It also proposes a new session typing system which allows a more liberal higher-order session communication based on an idea of Gay and Hole.

1 Introduction

Session primitives and types provide a flexible programming style for structural interaction, and are used to statically check the safe and consistent composition of protocols in communication-centric distributed software. They have been studied for the π-calculus [3, 10, 11, 12, 13, 17, 20], Ambients [5], CORBA interfaces [18], multi-threaded functional languages [20, 21], Web Description Languages [4], and distributed [7] and multi-threaded Java [6] and, at the industry level, WC3-CDL [22] and pi4Tech [16].

This paper reports on recent active discussions on the two fundamental theorems, Subject Reduction and Type Safety, among the authors of session types. In the presence of higher-order session communication, session instantiation dynamically changes the structure of sessions, so that it becomes non-trivial to preserve typability.

Unfortunately authors working on session types have recently realised that some of the previous systems fail to satisfy these basic theorems. Interestingly, the subtlety of type preservation is related to a treatment of communication

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channels in the rewriting rules of the π-calculus. After discussing the issues involved in higher-order session communication, this report also proposes a new session typing system which allows a more liberal higher-order session communication based on an idea of Gay and Hole [11].

The full proofs of the two theorems are firstly given in this report, which also clarifies some definitions absent in [12]. The motivation to why the present authors should redo the proofs nine years after is the discovery of a subtle counterexample to the results in some works on session types published after the work under consideration, although not to results of this original system. We explain the problem in detail in Section 3.

The new technical contributions of this report include: the formulation of recursive types, proofs for the Subject Reduction and Type Safety Theorems in the original session typing system by Honda-Vasconcelos-Kubo in ESOP'98, as well as the introduction of a new session typing system and proofs of the two theorems for this system.

The outline of the paper is simple. The next section revisites the ESOP'98 system, presenting proofs for the above mentioned results. Section 3 presents the more liberal system. Section 4 concludes the paper.

2 The Honda-Vasconcelos-Kubo Session Typing System in [12]

Honda-Vasconcelos-Kubo's session typing system in ESOP'98 is an extension of the first session typing system in [17] that allows higher-order session communication. We first review the syntax, operational semantics and typing system in [12] informally. We then state and prove the main theorems, Subject Reduction and Type Safety. Detailed examples and explanations of the language and typing system can be found in [12].

2.1 Syntax and Operational Semantics

A *session* is a series of reciprocal interactions between two parties, possibly with branching and recursion, and serves as a unit of abstraction for describing interaction. Communications belonging to a session are performed via a port specific to that session, called a *channel*. A fresh channel is generated when initiating each session, for the use in safe communications.

We use the following base sets: *names*, ranged over by $a, b, x, y, z \ldots$; *channels*, ranged over by k, k'; *constants* (including names, integers and booleans), ranged over by $c, c', \ldots$; *labels*, ranged over by $l, l', \ldots$; and *process variables*, ranged over by $X, Y, \ldots$ Letters $u, u', \ldots$ denote names and channels together. Then *processes*, ranged over by $P, Q \ldots$, and *expressions*, ranged over by $e, e', \ldots$ are given by the grammar in Figure 1.

The *bindings* for names are $k?(\tilde{x})$ `in` P and $(\nu a)P$; those for channels are `request` $a(k)$ `in` P, `accept` $a(k)$ `in` P and $(\nu k)P$; and that for process variables are `def` D `in` P. The derived notions of bound and free identifiers, alpha equivalence and substitution are standard. For P a process, $\mathrm{fpv}(P)$ denotes the set of free process variables, $\mathrm{fn}(P)$ denotes the set of free names, and $\mathrm{fc}(P)$ the set of free channels. We also need to talk about the set of process variables

$$
\begin{array}{rll}
P & ::= \texttt{request}\ a(k)\ \texttt{in}\ P & \text{session request} \\
& \mid \texttt{accept}\ a(k)\ \texttt{in}\ P & \text{session acceptance} \\
& \mid k![\tilde{e}]; P & \text{data sending} \\
& \mid k?(\tilde{x})\ \texttt{in}\ P & \text{data reception} \\
& \mid k \lhd l; P & \text{label selection} \\
& \mid k \rhd \{l_1 : P_1 [\!] \cdots [\!] l_n : P_n\} & \text{label branching} \\
& \mid \texttt{throw}\ k[k']; P & \text{channel sending} \\
& \mid \texttt{catch}\ k(k')\ \texttt{in}\ P & \text{channel reception} \\
& \mid \texttt{if}\ e\ \texttt{then}\ P\ \texttt{else}\ Q & \text{conditional branch} \\
& \mid P \mid Q & \text{parallel composition} \\
& \mid \texttt{inact} & \text{inaction} \\
& \mid (\nu u)P & \text{name/channel hiding} \\
& \mid \texttt{def}\ D\ \texttt{in}\ P & \text{recursion} \\
& \mid X[\tilde{e}\tilde{k}] & \text{process variables} \\
e & ::= c & \text{constant} \\
& \mid e + e' \ \mid\ e - e' \ \mid\ e \times e \ \mid\ \texttt{not}(e) \ \mid\ \ldots & \text{operators} \\
D & ::= X_1(\tilde{x}_1\tilde{k}_1) = P_1\ \texttt{and} \cdots \texttt{and}\ X_n(\tilde{x}_n\tilde{k}_n) = P_n & \text{declaration for recursion}
\end{array}
$$

Figure 1: Syntax

$$
\begin{array}{c}
P \mid \texttt{inact} \equiv P \qquad P \mid Q \equiv Q \mid P \qquad (P \mid Q) \mid R \equiv P \mid (Q \mid R) \\
(\nu u)P \mid Q \equiv (\nu u)(P \mid Q) \quad \text{if } u \notin \mathrm{fu}(Q) \\
(\nu u)\texttt{inact} \equiv \texttt{inact} \\
\texttt{def}\ D\ \texttt{in}\ \texttt{inact} \equiv \texttt{inact} \\
(\nu u)\texttt{def}\ D\ \texttt{in}\ P \equiv \texttt{def}\ D\ \texttt{in}\ (\nu u)P \quad \text{if } u \notin \mathrm{fu}(D) \\
(\texttt{def}\ D\ \texttt{in}\ P) \mid Q \equiv \texttt{def}\ D\ \texttt{in}\ (P \mid Q) \quad \text{if } \mathrm{dv}(D) \cap \mathrm{fpv}(Q) = \emptyset \\
\texttt{def}\ D\ \texttt{in}\ (\texttt{def}\ D'\ \texttt{in}\ P) \equiv \texttt{def}\ D\ \texttt{and}\ D'\ \texttt{in}\ P \quad \text{if } \mathrm{dv}(D) \cap \mathrm{dv}(D') = \emptyset.
\end{array}
$$

Figure 2: Structural Congruence

introduced in declarations $\mathrm{dv}(X_1(\tilde{x}_1\tilde{k}_1) = P_1\ \texttt{and} \cdots \texttt{and}\ X_n(\tilde{x}_n\tilde{k}_n) = P_n) = \{X_1, \ldots, X_n\}$.

Structural congruence is the smallest congruence relation on processes that include the equations in Figure 2. The operational semantics is given by the *reduction relation*, denoted $P \to Q$, the smallest relation on processes generated by the rules in Figure 3, where $e \downarrow c$ says that expression e evaluates to constant c.

Rule [Link] establishes a new session between the server $\texttt{accept}\ a(k)\ \texttt{in}\ P_1$ and the client $\texttt{request}\ a(k)\ \texttt{in}\ P_2$ via shared name a. Rule [Com] transmits values between the client and the server at the private channel so that determinacy

$$(\texttt{accept}\ a(k)\ \texttt{in}\ P_1) \mid (\texttt{request}\ a(k)\ \texttt{in}\ P_2) \ \rightarrow\ (\nu k)(P_1 \mid P_2) \qquad [\textsc{Link}]$$

$$(k![\tilde{e}]; P_1) \mid\ (k?(\tilde{x})\ \texttt{in}\ P_2) \ \rightarrow\ P_1 \mid P_2[\tilde{c}/\tilde{x}] \qquad (\tilde{e} \downarrow \tilde{c}) \qquad [\textsc{Com}]$$

$$(k \lhd l_i; P) \mid (k \rhd \{l_1 : P_1 [\!] \cdots [\!] l_n : P_n\}) \ \rightarrow\ P \mid\ P_i \ \ (1 \leq i \leq n) \qquad [\textsc{Label}]$$

$$(\texttt{throw}\ k[k']; P_1) \mid\ (\texttt{catch}\ k(k')\ \texttt{in}\ P_2) \ \rightarrow\ P_1 \mid\ P_2 \qquad [\textsc{Pass}]$$

$$\texttt{if}\ e\ \texttt{then}\ P_1\ \texttt{else}\ P_2 \ \rightarrow\ P_1 \qquad (e \downarrow \texttt{true}) \qquad [\textsc{If1}]$$

$$\texttt{if}\ e\ \texttt{then}\ P_1\ \texttt{else}\ P_2 \ \rightarrow\ P_2 \qquad (e \downarrow \texttt{false}) \qquad [\textsc{If2}]$$

$$\texttt{def}\ D\ \texttt{in}\ (X[\tilde{e}\tilde{k}] \mid Q) \ \rightarrow\ \texttt{def}\ D\ \texttt{in}\ (P[\tilde{c}/\tilde{x}] \mid Q)\ (\tilde{e} \downarrow \tilde{c}, X(\tilde{x}\tilde{k}) = P \in D) \qquad [\textsc{Def}]$$

$$P \rightarrow P' \ \Rightarrow\ (\nu u)P \rightarrow (\nu u)P' \qquad [\textsc{Scop}]$$

$$P \rightarrow P' \ \Rightarrow\ P \mid Q \ \rightarrow\ P' \mid Q \qquad [\textsc{Par}]$$

$$P \equiv P' \text{ and } P' \rightarrow Q' \text{ and } Q' \equiv Q \ \Rightarrow\ P \rightarrow Q \qquad [\textsc{Str}]$$

Figure 3: Reduction

of value delivery is ensured among two parties. Rule [Pass] is the key rule to allow *higher-order session communication*, i.e. session channel send and receive, with which various protocols are expressed, allowing complex nested structured communications. To show the difference between channels and names, for example,

$$\texttt{accept}\ a(k)\ \texttt{in}\ P_1 \mid \texttt{accept}\ a(k)\ \texttt{in}\ P_2 \mid \texttt{request}\ a(k)\ \texttt{in}\ Q$$

is accepted by the type system, while

$$\texttt{throw}\ k[k']; P_1 \mid \texttt{throw}\ k[k']; P_2 \mid \texttt{catch}\ k(k')\ \texttt{in}\ Q$$

is prohibited since the two senders at k appear in context at the same time.

Relationship with the Rewriting Rules of the π-Calculus. The essence of rule [Pass] is related to a "trick" in a rule of the operational semantics of a variant of the π-calculus, called the πI-calculus in the literature [15]. This calculus restricts name passing to bound (private) name passing. Syntactically it restricts outputs to processes to the form:

$$(\nu\tilde{y})(\overline{x}\langle\tilde{y}\rangle \mid P) \quad \text{with } \tilde{y} \text{ pairwise distinct} \qquad (1)$$

where $\tilde{y} = y_1 \ldots y_n$ denotes a potentially empty vector, $\mid$ denotes parallel composition, and $\overline{x}\langle\tilde{v}\rangle$ is an asynchronous output (or a message). We write the process in (1) as $\overline{x}(\tilde{y}).P$. The dynamics has the following form by the restriction to the bound output.

$$x(\tilde{y}).P \mid \overline{x}(\tilde{y}).Q \ \rightarrow\ (\nu\tilde{y})(P \mid Q) \qquad (2)$$

Note that $\tilde{y}$, present both in the input and in the output, indicates that α-conversion is implicitly performed ahead of communication. One can easily observe a similarity between this rule, and rules [Link] and [Pass]: channel k is always freshly generated in rule [Link] and channel k' in rule [Pass] is already created and bound at a previous interaction. Hence no substitution is performed in (2), [Link] or [Pass].

$$
\begin{array}{rrl}
\text{Sort} & S & ::= \mathsf{nat} \mid \mathsf{bool} \mid \langle \alpha, \overline{\alpha} \rangle \\
\text{Type} & \alpha & ::= ?[\tilde{S}]; \alpha \mid ?[\alpha]; \beta \mid \&\{l_1 \colon \alpha_1, \ldots, l_n \colon \alpha_n\} \mid \mathtt{end} \mid \bot \mid \\
& & \quad ![\tilde{S}]; \alpha \mid ![\alpha]; \beta \mid \oplus\{l_1 \colon \alpha_1, \ldots, l_n \colon \alpha_n\} \mid t \mid \mu t.\alpha
\end{array}
$$

Figure 4: The syntax of types

$$
\begin{array}{ccc}
\overline{![\tilde{S}]; \alpha} = ?[\tilde{S}]; \overline{\alpha} & \overline{\oplus\{l_i \colon \alpha_i\}_{i \in I}} = \&\{l_i \colon \overline{\alpha_i}\}_{i \in I} & \overline{![\alpha]; \beta} = ?[\alpha]; \overline{\beta} \\
\overline{?[\tilde{S}]; \alpha} = ![\tilde{S}]; \overline{\alpha} & \overline{\&\{l_i \colon \alpha_i\}_{i \in I}} = \oplus\{l_i \colon \overline{\alpha_i}\}_{i \in I} & \overline{?[\alpha]; \beta} = ![\alpha]; \overline{\beta} \\
\overline{\mathtt{end}} = \mathtt{end} & \overline{\mu t.\alpha} = \mu t.\overline{\alpha} & \overline{t} = t
\end{array}
$$

Figure 5: The co-type of a type

2.2 Type Discipline

Structured communication-based programming allows a clear description of complex interaction structures beyond conventional communication primitives. The more complex the interaction becomes, the more difficult it would be to capture the whole interactive behaviour and to write correct programs. The session type discipline offers a simple static checking framework to guarantee the correctness of communication patterns in such situations. It guarantees that well-typed programs are exempt from incompatibility in interaction patterns.

Types. Given a set of *type variables* ranged over by $t, t', \ldots$, the set $\mathcal{S}$ of *sorts* ranged over by $S, S', \ldots$, and the set $\mathcal{T}$ of *types* ranged over by $\alpha, \beta, \ldots$ are defined by the grammar in Figure 4.

The type $?[\tilde{S}]; \alpha$ represents the behaviour of first inputting values of sorts $\tilde{S}$, then performing the actions prescribed by type α; type $?[\alpha]; \beta$ represents a similar behaviour, which starts with channel input (catch) instead; types $![\tilde{S}]; \alpha$ and $![\alpha]; \beta$ are the dual of $?[\tilde{S}]; \alpha$ and $![\alpha]; \beta$, sending values instead of receiving. Type $\&\{l_1 \colon \alpha_1, \ldots, l_n \colon \alpha_n\}$ describes a branching behaviour: it waits with n options, and behave as type α_i if i-th action is selected (external choice); type $\oplus\{l_1 \colon \alpha_1, \ldots, l_n \colon \alpha_n\}$ then represents the behaviour which would select one of l_i and then behaves as α_i, according to the selected l_i (internal choice). Type $\mathtt{end}$ represents inaction, acting as the unit of sequential composition; $\mu t.\alpha$ denotes a recursive behaviour, representing the behaviour that starts by doing α and, when t is encountered, recurs to α again; and finally $\bot$ is a specific type indicating that no further interaction is possible at a given name.

For a type α in which $\bot$ does not occur, we define $\overline{\alpha}$, the *co-type* (or dual) of α, by exchanging ! and ?, and & and $\oplus$. The inductive definition is in Figure 5.

Recursive Types. One of the new contributions of the present abstract is a precise definition and the fixed point theorem on recursive types which were omitted from the original paper. The μ operator is a binder, giving rise, in the standard way, to notions of bound and free variables and alpha-equivalence.

Similarly to processes, we do not distinguish between alpha-convertible types. Furthermore, we take an *equi-recursive* view of types [14], not distinguishing between a type $\mu t.\alpha$ and its unfolding $\alpha[\mu t.\alpha/t]$. We are interested on *contractive types* only.

Definition 2.1 (Contractive) *A type is* contractive *if for each of its subexpressions $\mu t.\mu t_1 \dots \mu t_n.\alpha$, the body α is not t.*

Henceforth we assume all types to be contractive.

Definition 2.2 (Type equivalence) *Two types α and β are said to be equivalent if the pair (α, β) is in the largest fix point of the monotone function $F\colon \mathcal{P}(\mathcal{T} \times \mathcal{T}) \to \mathcal{P}(\mathcal{T} \times \mathcal{T})$ defined by:*

$$
\begin{aligned}
F(R) = {} & \{(\mathtt{end}, \mathtt{end}), (\bot, \bot)\} \\
& \cup \{(?[\tilde{S}]; \alpha, ?[\tilde{S}]; \beta) \mid (\alpha, \beta) \in R\} \\
& \cup \{(![\tilde{S}]; \alpha, ![\tilde{S}]; \beta) \mid (\alpha, \beta) \in R\} \\
& \cup \{(?[\alpha]; \beta, ?[\alpha']; \beta') \mid (\alpha, \alpha'), (\beta, \beta') \in R\} \\
& \cup \{(![\alpha]; \beta, ![\alpha']; \beta') \mid (\alpha, \alpha'), (\beta, \beta') \in R\} \\
& \cup \{(\oplus\{l_i\colon \alpha_i\}_{i\in I}, \oplus\{l_i\colon \beta_i\}_{i\in I}) \mid (\alpha_i, \beta_i) \in R, \forall i \in I\} \\
& \cup \{(\&\{l_i\colon \alpha_i\}_{i\in I}, \&\{l_i\colon \beta_i\}_{i\in I}) \mid (\alpha_i, \beta_i) \in R, \forall i \in I\} \\
& \cup \{(\mu t.\alpha, \beta) \mid (\alpha[\mu t.\alpha/t], \beta) \in R\} \\
& \cup \{(\alpha, \mu t.\beta) \mid (\alpha, \beta[\mu t.\beta/t]) \in R\}
\end{aligned}
$$

Theorem 2.3 *The largest fix point of function F is an equivalence relation.*

Proof. For each of the three cases (reflexivity, symmetry, transitivity) we follow [14], Theorems 21.3.6–7. Take symmetry. A relation R is symmetric if it is closed under the monotone function $\mathrm{Sym}(R) = \{(\alpha, \beta\}) \mid (\beta, \alpha) \in R\}$. We start by noting that (cf. [14], Theorem 21.3.6):

> $\mathrm{Sym}(F(R)) \subseteq F(\mathrm{Sym}(R))$ implies that the largest fixed point of F is symmetric.

We then show that $\mathrm{Sym}(F(R)) \subseteq F(\mathrm{Sym}(R))$. Let $(\alpha, \beta) \in \mathrm{Sym}(F(R))$. By definition of Sym, there exists $(\beta, \alpha) \in F(R)$. Our goal is to show that $(\beta, \alpha) \in F(\mathrm{Sym}(R))$. Consider all possible shapes of α. We focus on two cases; the remaining are similar.

Case $\alpha = \mathtt{end}$. Since $(\beta, \alpha) \in F(R)$, the definition of F implies that $\beta = \mathtt{end}$ or $\beta = \mu t.\gamma$ with $(\alpha, \gamma[\beta/t]) \in R$. In the first case, notice that $(\mathtt{end}, \mathtt{end}) \in F(R)$ for any R, in particular for $F(\mathrm{Sym}(R))$. In the second case, we know that $(\gamma[\beta/t], \alpha) \in \mathrm{Sym}(R)$ (by the definition of Sym), hence that $(\beta, \alpha) \in F(\mathrm{Sym}(R))$ (by the definition of F).

Case $\alpha = \&\{l_i\colon \alpha_i\}_{i\in I}$. Since $(\beta, \alpha) \in F(R)$, the definition of F implies that $\beta = \&\{l_i\colon \beta_i\}_{i\in I}$ or $\beta = \mu t.\gamma$ with $(\alpha, \gamma[\beta/t]) \in R$. In the first case, by the definition of Sym, we have $(\beta_i, \alpha_i) \in \mathrm{Sym}(R)$ for all $i \in I$, hence $(\&\{l_i\colon \beta_i\}_{i\in I}, \&\{l_i\colon \alpha_i\}_{i\in I}) \in F(\mathrm{Sym}(R))$. In the second case proceed as above. □

Henceforth types are understood up to type equivalence, so that, for example, in a typing derivation, types $\mu t.\alpha$ and $\alpha[\mu t.\alpha/t]$ are be used interchangeably. Due to the presence of record structures in the syntax of types ($\oplus\{l_1\colon \alpha_1, \ldots, l_n\colon \alpha_n\}$, $\&\{l_1\colon \alpha_1, \ldots, l_n\colon \alpha_n\}$), we do not pursue an interpretation of types as regular infinite trees (the interested reader may refer to [19] for such an interpretation).

$$\Gamma \cdot a\colon S \vdash a \triangleright S \quad \Gamma \vdash 1 \triangleright \mathsf{nat} \quad \Gamma \vdash \mathtt{true}, \mathtt{false} \triangleright \mathsf{bool} \quad \frac{\Gamma \vdash e_i \triangleright \mathsf{nat}}{\Gamma \vdash e_1 + e_2 \triangleright \mathsf{nat}}$$
[NameI],[Nat],[Bool],[Sum]

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \mathtt{end}}{\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \bot} \qquad \Theta; \Gamma \vdash \mathtt{inact} \triangleright \Delta$$
[Bot],[Inact]

$$\frac{\Gamma \vdash a \triangleright \langle \alpha, \overline{\alpha} \rangle \quad \Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \alpha}{\Theta; \Gamma \vdash \mathtt{accept}\ a(k)\ \mathtt{in}\ P \triangleright \Delta}$$
[Acc]

$$\frac{\Gamma \vdash a \triangleright \langle \alpha, \overline{\alpha} \rangle \quad \Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \overline{\alpha}}{\Theta; \Gamma \vdash \mathtt{request}\ a(k)\ \mathtt{in}\ P \triangleright \Delta}$$
[Req]

$$\frac{\Gamma \vdash \tilde{e} \triangleright \tilde{S} \quad \Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \alpha}{\Theta; \Gamma \vdash k![\tilde{e}]; P \triangleright \Delta \cdot k\colon ![\tilde{S}]; \alpha}$$
[Send]

$$\frac{\Theta; \Gamma \cdot \tilde{x}\colon \tilde{S} \vdash P \triangleright \Delta \cdot k\colon \alpha}{\Theta; \Gamma \vdash k?(\tilde{x})\ \mathtt{in}\ P \triangleright \Delta \cdot k\colon ?[\tilde{S}]; \alpha}$$
[Rcv]

$$\frac{\Theta; \Gamma \vdash P_1 \triangleright \Delta \cdot k\colon \alpha_1 \quad \cdots \quad \Theta; \Gamma \vdash P_n \triangleright \Delta \cdot k\colon \alpha_n}{\Theta; \Gamma \vdash \ k \triangleright \{l_1 : P_1 [\!] \cdots [\!] l_n : P_n\} \triangleright \Delta \cdot k\colon \&\{l_1\colon \alpha_1, \ldots, l_n\colon \alpha_n\}}$$
[Br]

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \alpha_j}{\Theta; \Gamma \vdash k \lhd l_j; P \triangleright \Delta \cdot k\colon \ \oplus \{l_1\colon \alpha_1, \ldots, l_n\colon \alpha_n\}} \quad (1 \leq j \leq n)$$
[Sel]

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \beta}{\Theta; \Gamma \vdash \mathtt{throw}\ k[k']; P \triangleright \Delta \cdot k\colon ![\alpha]; \beta \cdot k'\colon \alpha}$$
[Thr]

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \beta \cdot k'\colon \alpha}{\Theta; \Gamma \vdash \mathtt{catch}\ k(k')\ \mathtt{in}\ P \triangleright \Delta \cdot k\colon ?[\alpha]; \beta}$$
[Cat]

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta \quad \Theta; \Gamma \vdash Q \triangleright \Delta'}{\Theta; \Gamma \vdash P \mid Q \triangleright \Delta \circ \Delta'} (\Delta \asymp \Delta')$$
[Conc]

$$\frac{\Gamma \vdash e \triangleright \mathsf{bool} \quad \Theta; \Gamma \vdash P \triangleright \Delta \quad \Theta; \Gamma \vdash Q \triangleright \Delta}{\Theta; \Gamma \vdash \mathtt{if}\ e\ \mathtt{then}\ P\ \mathtt{else}\ Q \triangleright \Delta}$$
[If]

$$\frac{\Theta; \Gamma \cdot a\colon S \vdash P \triangleright \Delta}{\Theta; \Gamma \vdash (\nu a)P \triangleright \Delta} \qquad \frac{\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \bot}{\Theta; \Gamma \vdash \ (\nu k)P \triangleright \Delta}$$
[NRes],[CRes]

$$\frac{\Gamma \vdash \tilde{e} \triangleright \tilde{S}}{\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash X[\tilde{e}\tilde{k}] \triangleright \Delta \cdot \tilde{k}\colon \tilde{\alpha}}$$
[Var]

$$\frac{\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \cdot \tilde{x}\colon \tilde{S} \vdash P \triangleright \tilde{k}\colon \tilde{\alpha} \quad \Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash Q \triangleright \Delta}{\Theta; \Gamma \vdash \mathtt{def}\ X(\tilde{x}\tilde{k}) = P\ \mathtt{in}\ Q \triangleright \Delta}$$
[Def]

Figure 6: Typing System

Typing System. A *sorting* (resp. a *typing*, resp. a *basis*) is a finite partial map from names to sorts (resp. from channels to types, resp. from variables to

sequences of sorts and types). We let $\Gamma, \Gamma', \ldots$ (resp. $\Delta, \Delta', \ldots$, resp. $\Theta, \Theta', \ldots$) range over sortings (resp. typings, resp. bases).

Definition 2.4 (Type algebra) *Typings* Δ_0 *and* Δ_1 *are* compatible*, written* $\Delta_0 \asymp \Delta_1$*, if* $\Delta_0(k) = \overline{\Delta_1(k)}$ *for all* $k \in \mathrm{dom}(\Delta_0) \cap \mathrm{dom}(\Delta_1)$*. When* $\Delta_0 \asymp \Delta_1$*, the* composition of Δ_0 and Δ_1*, written* $\Delta_0 \circ \Delta_1$*, is given as a typing such that* $(\Delta_0 \circ \Delta_1)(k)$ *is (1)* $\bot$*, if* $k \in \mathrm{dom}(\Delta_0) \cap \mathrm{dom}(\Delta_1)$*; (2)* $\Delta_i(k)$*, if* $k \in \mathrm{dom}(\Delta_i) \setminus \mathrm{dom}(\Delta_{i+1 \bmod 2})$ *for* $i \in \{0, 1\}$*; and (3) undefined otherwise.*

We write $\Delta \cdot k \colon \alpha$ when $k \notin \mathrm{dom}(\Delta)$, and $\Delta, k \colon \alpha$ when k may be in $\mathrm{dom}(\Delta)$. This notation is then extended to $\Delta \cdot \Delta'$. Also, $\Theta \setminus x$ denotes the result of taking off $x \colon \Theta(x)$ from Θ. Similarly for $\Gamma \setminus a$ and for $\Delta \setminus k$.

Typing judgement are of the form $\Theta; \Gamma \vdash P \triangleright \Delta$ which reads: "under the environment $\Theta; \Gamma$, process P has typing Δ". The typing system is defined by the axioms and rules in Figure 6, where we assume that the range of Δ in [Inact] and [Var] contains `end` and $\bot$ only. We also simplify the recursive definition to the single case; the extension to the multiple recursion is obvious.

2.3 Changes from the ESOP'98 system

For the syntax, we added $x, y, z, \ldots$ to the category of names, thus incorporating the set of variables into that of names. We have made clear the notions of bindings for the various identifiers in the calculus. For the structural congruence relation, we have replaced $\mathrm{fpv}(D)$ by $\mathrm{dv}(D)$, the set of variables introduced in declaration D, and we added rule `def` D `in inact` $\equiv$ `inact` for flexibility. For types, we changed the syntax from `1` to `end`, from $\uparrow$ to !, and from $\downarrow$ to ?, following [11]. We have also added more accurate definitions for recursive types (Definitions 2.1 and 2.2) for clarification. For the typing system, we added [NameI], [Nat], [Bool], [Sum] and revised [Acc], [Req], [Var], [Def]. All of these changes are improvements and do not imply any technical difference with respect to [12].

However there is one important addition with respect to the typing system in [12]: the [Bot]-rule. Without the [Bot]-rule, subject congruence (Lemma 2.9) does not hold. Take for example process `throw` $k[k']$; `inact` | `inact` structural congruent to `throw` $k[k']$; `inact`. We have

$$\vdash \texttt{throw}\ k[k']; \texttt{inact} \mid \texttt{inact} \triangleright k \colon ![\texttt{end}]; \texttt{end} \cdot k' \colon \bot$$

but process `throw` $k[k']$; `inact` is not typable under the *same typing* [2]. In [3], the authors fixed the problem by adding the condition $\beta \neq$ `end` in the [Thr]-rule. We believe the solution herein presented offers extra flexibility.

2.4 Subject Reduction and Type Safety

To simplify the statement of our results and their proofs, we make use of the *variable convention* [1], allowing, for example, to assume that in sequent $\Theta; \Gamma \vdash P \triangleright \Delta \cdot k \colon \alpha$, channel k is not bound in P.

We start with a few auxiliary results; Subject-Reduction is in page 10, and Type Safety in page 12.

Lemma 2.5 (Weakening Lemma) *Let* $\Theta; \Gamma \vdash P \triangleright \Delta$.

1. *If* $X \notin \mathrm{dom}(\Theta)$*, then* $\Theta, X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash P \triangleright \Delta$.

2. *If* $a \notin \mathrm{dom}(\Gamma)$*, then* $\Theta; \Gamma, a\colon S \vdash P \triangleright \Delta$.

3. *If* $k \notin \mathrm{dom}(\Delta)$ *and* $\alpha = \bot$ *or* $\alpha = \mathtt{end}$*, then* $\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \alpha$.

Proof. A simple induction on the derivation tree of each sequent. For (3), we note in [Inact] and [Var], Δ contains only `end` and $\bot$. □

Lemma 2.6 (Strengthening Lemma) *Let* $\Theta; \Gamma \vdash P \triangleright \Delta$.

1. *If* $X \notin \mathrm{fpv}(P)$*, then* $\Theta \setminus X; \Gamma \vdash P \triangleright \Delta$.

2. *If* $a \notin \mathrm{fn}(P)$*, then* $\Theta; \Gamma \setminus a \vdash P \triangleright \Delta$.

3. *If* $k \notin \mathrm{fc}(P)$*, then* $\Theta; \Gamma \vdash P \triangleright \Delta \setminus k$.

Proof. Standard. □

Lemma 2.7 (Channel Lemma) 1. $\Theta; \Gamma \vdash P \triangleright \Delta \cdot k\colon \alpha$ *and* $k \notin \mathrm{fc}(P)$ *implies* $\alpha = \bot, \mathtt{end}$.

2. $\Theta; \Gamma \vdash P \triangleright \Delta$ *and* $k \in \mathrm{fc}(P)$ *implies* $k \in \mathrm{dom}(\Delta)$.

Proof. A simple induction on the derivation tree for each sequent. □

We omit the standard renaming properties of variables and channels, but present the Substitution Lemma for names. Note that we do *not* require a substitution lemma for channels or process variables.

Lemma 2.8 (Substitution Lemma) $\Theta; \Gamma, x\colon S \vdash P \triangleright \Delta$ *and* $\Theta; \Gamma \vdash c\colon S$ *implies* $\Theta; \Gamma \vdash P[c/x] \triangleright \Delta$

Proof. Standard. □

We write $\Delta \prec \Delta'$ if we obtain Δ' from Δ by replacing $k_1\colon \mathtt{end}, ..., k_n\colon \mathtt{end}$ ($n \geq 0$) in Δ by $k_1\colon \bot, ..., k_n\colon \bot$. If $\Delta \prec \Delta'$, we can obtain Δ' from Δ by applying the [Bot]-rule zero or more.

Lemma 2.9 (Subject Congruence) $\Theta; \Gamma \vdash P \triangleright \Delta$ *and* $P \equiv Q$ *imply* $\Theta; \Gamma \vdash Q \triangleright \Delta$.

Proof. **Case** $P \mid \mathtt{inact} \equiv P$**.** We show that if $\Theta; \Gamma \vdash P \mid \mathtt{inact} \triangleright \Delta$, then $\Theta; \Gamma \vdash P \triangleright \Delta$. Suppose

$$\Theta; \Gamma \vdash P \triangleright \Delta_1 \quad \text{and} \quad \Theta; \Gamma \vdash \mathtt{inact} \triangleright \Delta_2.$$

with $\Delta_1 \circ \Delta_2 = \Delta$. Note that Δ_2 only contains `end` or $\bot$, hence we can set: $\Delta_1 = \Delta_1' \circ \{\tilde{k}\colon \tilde{\mathtt{end}}\}$ and $\Delta_2 = \Delta_2' \cdot \{\tilde{k}\colon \tilde{\mathtt{end}}\}$ with $\Delta_1' \circ \Delta_2' = \Delta_1' \cdot \Delta_2'$ and $\Delta = \Delta_1' \cdot \Delta_2' \cdot \{\tilde{k}\colon \tilde{\bot}\}$. Then by the [Bot]-rule, we have:

$$\Theta; \Gamma \vdash P \triangleright \Delta_1' \cdot \{\tilde{k}\colon \tilde{\bot}\}$$

Note that by the variable convention, the names in Δ_2 are not bound in P, for they cannot be free (in Δ_2) and bound (in P) at the same time. Hence by applying Weakening, we have:

$$\Theta; \Gamma \vdash P \triangleright \Delta_1' \cdot \Delta_2' \cdot \{\tilde{k}\colon \tilde{\bot}\}$$

as required.
For the other direction, we set $\Delta = \emptyset$ in [Inact].
Case $P \mid Q \equiv Q \mid P$, $(P \mid Q) \mid R \equiv P \mid (Q \mid R)$**.** By commutativity and associativity of $\asymp$.
Case $(\nu u)P \mid Q \equiv (\nu u)(P \mid Q)$ if $u \notin \mathrm{fu}(Q)$**.** The case when u is a name is standard. Suppose u is channel k and assume $\Theta; \Gamma \vdash (\nu k)(P \mid Q) \triangleright \Delta$. We have

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta_1' \qquad \Theta; \Gamma \vdash Q \triangleright \Delta_2'}{\Theta; \Gamma \vdash P \mid Q \triangleright \Delta' \cdot k\colon \bot}$$

with $\Delta' \cdot k\colon \bot = \Delta_1' \circ \Delta_2'$, and $\Delta' \prec \Delta$ by [Bot]. First notice that k can be in either Δ_i' or in both. The interesting case is when it occurs in both; from Lemma 2.7(1) and the fact that $k \notin \mathrm{fc}(Q)$ we know that $\Delta_1' = \Delta_1 \cdot k\colon \mathtt{end}$ and $\Delta_2' = \Delta_2 \cdot k\colon \mathtt{end}$. Then, by applying the [Bot]-rule to k in P, we have $\Theta; \Gamma \vdash P \triangleright \Delta_1 \cdot k\colon \bot$, and by applying [CRes] we obtain $\Theta; \Gamma \vdash (\nu k)P \triangleright \Delta_1$. On the other hand, by Strengthening, we have $\Theta; \Gamma \vdash Q \triangleright \Delta_2$. Then, the application of [Par] yields $\Theta; \Gamma \vdash (\nu k)P \mid Q \triangleright \Delta'$. Then by applying the [Bot]-rule, we obtain $\Theta; \Gamma \vdash (\nu k)P \mid Q \triangleright \Delta$, as required. The other direction is easy.
Case $(\nu u)\mathtt{inact} \equiv \mathtt{inact}$**.** Standard by Weakening and Strengthening.
Case $\mathtt{def}\ D\ \mathtt{in}\ \mathtt{inact} \equiv \mathtt{inact}$**.** Similar to the first case using Weakening and Strengthening.
Case $(\nu u)\mathtt{def}\ D\ \mathtt{in}\ P \equiv \mathtt{def}\ D\ \mathtt{in}\ (\nu u)P$ if $u \notin \mathrm{fu}(D)$**.** Similar to the scope opening case using Weakening and Strengthening.
Case $(\mathtt{def}\ D\ \mathtt{in}\ P) \mid Q \equiv \mathtt{def}\ D\ \mathtt{in}\ (P \mid Q)$ if $\mathrm{dv}(D) \cap \mathrm{fpv}(Q) = \emptyset$**.** Similar with the scope opening case using Weakening and Strengthening. □

Theorem 2.10 (Subject Reduction) $\Theta; \Gamma \vdash P \triangleright \Delta$ *and* $P \to^* Q$ *imply* $\Theta; \Gamma \vdash Q \triangleright \Delta$.

Proof. We assume that

$$\Theta; \Gamma \vdash e \triangleright S \quad \text{and} \quad e \downarrow c \quad \text{implies} \quad \Theta; \Gamma \vdash c \triangleright S \tag{3}$$

and prove the result by induction on the last rule applied.
Case [Link] $(\mathtt{accept}\ a(k)\ \mathtt{in}\ P_1) \mid (\mathtt{request}\ a(k)\ \mathtt{in}\ P_2) \to (\nu k)(P_1 \mid P_2)$**.** Suppose $\Theta; \Gamma \vdash (\mathtt{accept}\ a(k)\ \mathtt{in}\ P) \mid (\mathtt{request}\ a(k)\ \mathtt{in}\ Q) \triangleright \Delta$. Then the assumption is derived from:

$$\frac{\Gamma \vdash a \triangleright \langle \alpha, \overline{\alpha} \rangle \quad \Theta; \Gamma \vdash P \triangleright \Delta_1 \cdot k\colon \alpha}{\Theta; \Gamma \vdash \mathtt{accept}\ a(k)\ \mathtt{in}\ P \triangleright \Delta_1} \text{ and } \frac{\Gamma \vdash a \triangleright \langle \alpha, \overline{\alpha} \rangle \quad \Theta; \Gamma \vdash Q \triangleright \Delta_2 \cdot k\colon \overline{\alpha}}{\Theta; \Gamma \vdash \mathtt{request}\ a(k)\ \mathtt{in}\ Q \triangleright \Delta_2}$$

and [Par] with $\Delta_1 \circ \Delta_2 = \Delta'$, and [Bot] with $\Delta' \prec \Delta$. Then applying [Par] to P and Q, we have:

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta_1 \cdot k\colon \alpha \quad \Theta; \Gamma \vdash Q \triangleright \Delta_2 \cdot k\colon \overline{\alpha}}{\Theta; \Gamma \vdash P \mid Q \triangleright \Delta' \cdot k\colon \bot}$$

Now applying [CRes] and [Bot], we are done.

Case [Com] $(k![\tilde{e}]; P_1) \mid (k?(\tilde{x})\ \texttt{in}\ P_2) \rightarrow P_1 \mid P_2[\tilde{c}/\tilde{x}]$ with $\tilde{e} \downarrow \tilde{c}$**.** The assumption is derived from:

$$\frac{\Gamma \vdash \tilde{e} \triangleright \tilde{S} \quad \Theta; \Gamma \vdash P_1 \triangleright \Delta_1 \cdot k\colon \alpha}{\Theta; \Gamma \vdash k![\tilde{e}]; P \triangleright \Delta_1 \cdot k\colon ![\tilde{S}]; \alpha} \text{ and } \frac{\Theta; \Gamma \cdot \tilde{x}\colon \tilde{S} \vdash P_2 \triangleright \Delta_2 \cdot k\colon \overline{\alpha}}{\Theta; \Gamma \vdash k?(\tilde{x})\ \texttt{in}\ Q \triangleright \Delta_2 \cdot k\colon ?[\tilde{S}]; \overline{\alpha}}$$

and [Par] with $\Delta_1 \circ \Delta_2 \cdot k\colon \bot = \Delta'$ and [Bot] with $\Delta' \prec \Delta$. Then by (3), we know $\Gamma \vdash \tilde{c} \triangleright \tilde{S}$. By applying Substitution Lemma, we have:

$$\Theta; \Gamma \vdash P_2[\tilde{c}/\tilde{x}] \triangleright \Delta_2 \cdot k\colon \overline{\alpha}$$

Now the application of [Par] to P_1 and $P_2[\tilde{c}/\tilde{x}]$ completes this case.

Case [Label] $(k \lhd l_i; P_1) \mid (k \rhd \{l_1 : P_1 [\!] \cdots [\!] l_n : P_n\}) \rightarrow P \mid P_i \ \ (1 \leq i \leq n)$**.** Similar to the above case.

Case [Pass] $(\texttt{throw}\ k[k']; P_1) \mid (\texttt{catch}\ k(k')\ \texttt{in}\ P_2) \rightarrow P_1 \mid P_2$**.** The assumption is derived from:

$$\frac{\Theta; \Gamma \vdash P_1 \triangleright \Delta_1 \cdot k\colon \beta}{\Theta; \Gamma \vdash \texttt{throw}\ k[k']; P \triangleright \Delta_1 \cdot k\colon ![\alpha]; \beta \cdot k'\colon \alpha}$$

and

$$\frac{\Theta; \Gamma \vdash P_2 \triangleright \Delta_2 \cdot k\colon \overline{\beta} \cdot k'\colon \alpha}{\Theta; \Gamma \vdash \texttt{catch}\ k(k')\ \texttt{in}\ Q \triangleright \Delta_2 \cdot k\colon ?[\alpha]; \overline{\beta}}$$

and [Par] with $\Delta_1 \circ \Delta_2 \cdot k\colon \bot \cdot k'\colon \alpha = \Delta'$ and [Bot] with $\Delta' \prec \Delta$. Note that $k, k' \notin \mathrm{dom}(\Delta_1, \Delta_2)$. By applying [Par] to P_1 and P_2, and then by [Bot], we obtain the required result.

Case [If1],[If2]**.** Trivial.

Case [Def] $\texttt{def}\ D\ \texttt{in}\ (X[\tilde{e}\tilde{k}] \mid Q) \rightarrow \texttt{def}\ D\ \texttt{in}\ (P_1[\tilde{c}/\tilde{x}] \mid Q)$ with $\tilde{e} \downarrow \tilde{c}$ and $X(\tilde{x}\tilde{k}) = P_1 \in D$**.** Simplifying the recursive definition to the single case, we set $D = (X(\tilde{x}\tilde{k}) = P_1)$. Then the assumption is derived from: c

$$\frac{\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \cdot \tilde{x}\colon \tilde{S} \vdash P \triangleright \tilde{k}\colon \tilde{\alpha} \qquad \dfrac{\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash X[\tilde{e}\tilde{k}] \triangleright \Delta_1' \cdot \tilde{k}\colon \tilde{\alpha} \quad \Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash Q \triangleright \Delta_2'}{\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash X[\tilde{e}\tilde{k}] \mid Q \triangleright \Delta' \cdot \tilde{k}\colon \tilde{\alpha}}}{\Theta; \Gamma \vdash \texttt{def}\ X(\tilde{x}\tilde{k}) = P\ \texttt{in}\ (X[\tilde{e}\tilde{k}] \mid Q) \triangleright \Delta' \cdot \tilde{k}\colon \tilde{\alpha}}$$

with $\Delta_0 = \Delta' \cdot \tilde{k}\colon \tilde{\alpha}$, $\Delta' = \Delta_1' \circ \Delta_2'$ and $\Delta_0 \prec \Delta$. Note that Δ_1' only contains $\bot$ or $\texttt{end}$. Then applying Substitution Lemma to P, we have:

$$\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash P[\tilde{c}/\tilde{x}] \triangleright \tilde{k}\colon \tilde{\alpha}$$

Then by Weakening, we have:

$$\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash P[\tilde{c}/\tilde{x}] \triangleright \Delta_1' \cdot \tilde{k}\colon \tilde{\alpha}$$

Now by [Par], we have

$$\Theta \cdot X\colon \tilde{S}\tilde{\alpha}; \Gamma \vdash P[\tilde{c}/\tilde{x}] \mid Q \triangleright \Delta' \cdot \tilde{k}\colon \tilde{\alpha}$$

Finally by [Def], we obtain:

$$\Theta; \Gamma \vdash \texttt{def}\ X(\tilde{x}\tilde{k}) = P\ \texttt{in}\ (P[\tilde{c}/\tilde{x}] \mid Q) \triangleright \Delta' \cdot \tilde{k}\colon \tilde{\alpha}$$

Then we can apply [Bot] to obtain Δ, as desired.
Case [Str]**.** By Subject-Congruence. □

To formalise Type Safety, we need the following notion: a *k-process* is a prefixed process with subject k (such as $k![\tilde{e}]; P$ and $\texttt{catch}\ k(k')\ \texttt{in}\ P$). Next, a *k-redex* is a pair of dual k-processes composed by $|$, i.e. either of forms $(k![\tilde{e}]; P \mid k?(\tilde{x})\ \texttt{in}\ Q)$, $(k \lhd l; P \mid k \rhd \{l_1 : Q_1 [\!] \cdots [\!] l_n : Q_n\})$, or $(\texttt{throw}\ k[k']; P \mid \texttt{catch}\ k(k'')\ \texttt{in}\ Q)$. Then P is an *error* if $P \equiv (\nu\tilde{u})(\texttt{def}\ D\ \texttt{in}\ (Q \mid R))$ where Q is, for some k, the $|$-composition of *either* two k-processes that do not form a k-redex, *or* three or more k-processes. We then have:

Theorem 2.11 (Type Safety) *A typable program never reduces into an error.*

Proof. By Subject Reduction it suffices to show that typable programs are not errors. The proof is by reductio ad absurdum, assuming error processes typable. Suppose that $\Theta; \Gamma \vdash \texttt{def}\ D\ \texttt{in}\ (\nu\tilde{u})(P \mid Q) \triangleright \Delta$. Analyzing the derivation tree for the process, we conclude that $\Theta; \Gamma \vdash P \triangleright \Delta'$, for some Δ'. We now analyze the two classes of error processes.

When $P = P_1 \mid P_2$ is the $|$-composition of two k-processes that do not form a redex, there are several cases to consider. They are all alike; take for example the pair label-select/throw. Applying [Par] on P, we have $\Theta; \Gamma \vdash P_1 \triangleright \Delta_1'$ and $\Theta; \Gamma \vdash P_2 \triangleright \Delta_2'$ with $\Delta' \prec \Delta_1' \circ \Delta_2'$. Applying [Sel] on P_1 and [Thr] on P_2 we conclude that $k\colon \oplus\{l_1\colon \alpha_1, \ldots, l_n\colon \alpha_n\} \in \Delta_1'$ and $k\colon ![\alpha]; \beta \in \Delta_2'$. But then $\Delta_1' \circ \Delta_2'$ is not defined, hence $\texttt{def}\ D\ \texttt{in}\ (\nu\tilde{u})(P \mid Q)$ is not typable.

When P is the the $|$-composition of three or more k-processes, we concentrate on the case of three processes, for the remaining cases reduce to this. So let $P = (P_1 \mid P_2) \mid P_3$. Applying [Par], we know that $\Theta; \Gamma \vdash P_1 \mid P_2 \triangleright \Sigma$ and $\Theta; \Gamma \vdash P_3 \triangleright \Sigma'$ with $\Delta' \prec \Sigma \circ \Sigma'$. If $P_1 \mid P_2$ is not a k-redex, we use the case above. Otherwise, it must be the case that $k\colon \bot \in \Sigma$. From Lemma 2.7(2), we know that $k \in \operatorname{dom} \Sigma'$, thus $\Sigma \circ \Sigma'$ is not defined, hence $\texttt{def}\ D\ \texttt{in}\ (\nu\tilde{u})(P \mid Q)$ is not typable. □

3 A More Liberal Session Passing Style

Rule [Pass] in the original ESOP'98 system:

$$(\texttt{throw}\ k[k']; P_1) \mid\ (\texttt{catch}\ k(k')\ \texttt{in}\ P_2)\ \rightarrow\ P_1 \mid\ P_2$$

does not allow the transmission of a channel the client is not expecting: it is explicit in the code of `accept` that the channel "received" must be k'. Channel passing, in this setting, reflects an agreement between the sender (`throw`) and the receiver (`catch`) whereby the former ceases to use channel k' and the latter may start using the channel: a form of "token passing", only he who holds the token may read or write into the channel.

A more liberal rule would allow the transmission of an arbitrary channel, implying a substitution on the client side.

$$(\texttt{throw}\ k[k']; P_1) \mid\ (\texttt{catch}\ k(k'')\ \texttt{in}\ P_2)\ \rightarrow\ P_1 \mid\ P_2[k'/k'']$$

Unfortunately this rule breaks Subject Reduction (Theorem 2.10). A counter-example is a process which, possessing one end of a channel, receives the second end. The process:

$$\texttt{throw}\ k[k'] \mid \texttt{catch}\ k(k'')\ \texttt{in}\ k''?(y)\ \texttt{in}\ k'![1] \tag{4}$$

is typable under typing $k\colon\ \bot, k'\colon \bot$, but reduces to process

$$k'?(x)\ \texttt{in}\ k'![1]$$

which is not typable under the *same typing* [6].

The question arises as whether the contractum can be typed, in general, with a different typing. In the above case and for the `catch` process in the redex, we have $k'\colon ![\mathsf{nat}].\mathtt{end}$, and $k''\colon ?[\mathsf{nat}].\mathtt{end}$. In the contract, channels k' and k'' are aliased and it is not obvious how to build, from the premises, the correct type $?[\mathsf{nat}].![\mathsf{nat}].\mathtt{end}$ for k'.

A solution, due to Gay and Hole, explicitly distinguishes between the two ends of a channel [11]. For a channel κ, its two ends are denoted κ^+ and κ^-. Channels are now runtime entities (they are not supposed to occur in programs) created by rule [Link], which becomes:

$$(\texttt{accept}\ a(x)\ \texttt{in}\ P_1) \mid (\texttt{request}\ a(x)\ \texttt{in}\ P_2)\ \rightarrow\ (\nu\kappa)(P_1[\kappa^+/x] \mid P_2[\kappa^-/x])$$

Rules that synchronize two processes on a given channel are updated so that each process explicitly mentions one of the ends. For example rule [Thr] becomes:

$$(\texttt{throw}\ \kappa^p[k'];P_1) \mid (\texttt{catch}\ \kappa^{\overline{p}}(x)\ \texttt{in}\ P_2)\ \rightarrow\ P_1 \mid P_2[k'/x]$$

where p denotes one end (one *polarity*) of κ and $\overline{p}$ the other.

A further change allows a typing Δ to contain one type for κ^+ and a different type (not necessarily dual) for κ^-. Parallel composition juxtaposes the typings of the two operands (provided they have disjoint domains), rather than composing using $\circ$ (cf. Definition 2.4).

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \quad \Theta;\Gamma \vdash Q \triangleright \Delta'}{\Theta;\Gamma \vdash P \mid Q \triangleright \Delta \cdot \Delta'} \qquad [\textsc{Par}]$$

An immediate consequence of the new rule is that we do not need the bottom $\bot$ type anymore, or the notions of typing compatibility and composition. One the other hand, the new rule for channel restriction requires the two ends of the channel to be of dual types.

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \cdot \kappa^+\colon \alpha \cdot k^-\colon \overline{\alpha}}{\Theta;\Gamma \vdash\ (\nu\kappa)P \triangleright \Delta} \qquad [\textsc{CRes}]$$

Notice the original rule (in Figure 6) requires an entry $k\colon \bot$ in typing Δ.

To understand how the new system works, consider process (4) refined into the new syntax:

$$\texttt{throw}\ k^+[k'^+] \mid \texttt{catch}\ k^-(x)\ \texttt{in}\ x?(y)\ \texttt{in}\ k'^-![1]$$

The process is typable under the typing $k^+ : ![\alpha]; \mathtt{end}, k^- : ?[\alpha]; \mathtt{end}, k'^+ : \alpha, k'^- : \overline{\alpha}$ where α is the type $?[\mathsf{nat}]; \mathtt{end}$. It now reduces to

$$k'^+?(x)\ \mathtt{in}\ k'^-![1]$$

which is still typable (this time under typing $k'^+ : \alpha, k'^- : \overline{\alpha}$).

Clearly, typability over arbitrary channel environments is not closed under reduction any more. For example, the process

$$k^+![\mathtt{true}] \mid k^-?(x)\ \mathtt{in}\ k'^-![x+1] \tag{5}$$

is typable under typing $k^+ : ![\mathsf{bool}]; \mathtt{end}, k^- : ?[\mathsf{nat}]; \mathtt{end}, k'^- : ![\mathsf{nat}]; \mathtt{end}$, but reduces to

$$k'^-![\mathtt{true}+1]$$

which is not typable. The last step is then to consider, for Subject Reduction and Type Safety purposes only typings where the two ends of a channel are of dual types. We call such typings *balanced*. This restriction rules out the above typing (since $![\mathsf{bool}]; \mathtt{end}$ is not dual to $?[\mathsf{nat}]; \mathtt{end}$), hence process (5) is not guaranteed to preserve typability under reduction or to be type safe.

3.1 Syntax and Operational Semantics

With respect to the syntax in Figure 1, we let κ, rather than k, range over *channels*. Identifier k now stands for polarized channels (κ^+, κ^-) or names (a, x). As such k cannot occur in a binding position anymore; three process constructors need to be updated: `accept`, `request`, and `catch`. The grammar of the language is given by the rules in Figure 1, replacing the productions for `accept`, `request`, and `catch` by the ones below.

$$\begin{array}{rll}
P & ::= \mathtt{request}\ a(x)\ \mathtt{in}\ P & \text{session request} \\
& \mid \mathtt{accept}\ a(x)\ \mathtt{in}\ P & \text{session acceptance} \\
& \mid \mathtt{catch}\ k(x)\ \mathtt{in}\ P & \text{channel reception} \\
& \mid \ldots & \\
k & ::= x \mid \kappa^p & \text{channel variables and values} \\
p & ::= + \mid - & \text{channel polarities}
\end{array}$$

Duality on polarities is defined as $\overline{+} = -$ and $\overline{-} = +$. Variable x is now bound in any of $\mathtt{request}\ a(x)\ \mathtt{in}\ P$, $\mathtt{accept}\ a(x)\ \mathtt{in}\ P$ and $\mathtt{catch}\ k(x)\ \mathtt{in}\ P$. This is in contrast to the original syntax, in which k is not bound in request a(k) etc.

The new reduction relation adapts the four rules that directly work with channels. Reduction is given by replacing, in Figure 3, rules [Link], [Com], [Label], and [Pass], by the four rules below. Structural congruence (Figure 2) remains unchanged.

$$(\mathtt{accept}\ a(x)\ \mathtt{in}\ P_1) \mid (\mathtt{request}\ a(x)\ \mathtt{in}\ P_2) \ \rightarrow (\nu\kappa)(P_1[\kappa^+/x] \mid P_2[\kappa^-/x]) \qquad [\textsc{Link}]$$

$$(\kappa^p![\tilde{e}]; P_1) \mid \ (\kappa^{\overline{p}}?(\tilde{x})\ \mathtt{in}\ P_2) \ \rightarrow \ P_1 \mid P_2[\tilde{c}/\tilde{x}] \qquad (\tilde{e} \downarrow \tilde{c}) \qquad [\textsc{Com}]$$

$$(\kappa^p \lhd l_i; P) \mid (\kappa^{\overline{p}} \rhd \{l_1 : P_1 [\!] \cdots [\!] l_n : P_n\}) \ \rightarrow \ P \mid \ P_i \qquad (1 \leq i \leq n) \quad [\textsc{Label}]$$

$$(\mathtt{throw}\ \kappa^p[\kappa'^q]; P_1) \mid \ (\mathtt{catch}\ \kappa^{\overline{p}}(x)\ \mathtt{in}\ P_2) \ \rightarrow \ P_1 \mid \ P_2[\kappa'^q/x] \qquad [\textsc{Pass}]$$

3.2 Type Discipline

Types in Figure 4 remain unchanged, except that bottom $\bot$ is no longer needed. Typings still feature entries of the form $k\colon \alpha$, only that k can now be a name x, or a polarized channel κ^+ or κ^-. The type system needs adjustments in rules [Acc], [Req], and [Cat] due to the change in syntax. Also, the absence of rule [Bot] is compensated by a new rule [CRes'] for $(\nu\kappa)P$. The main change however happens in rules [Conc] and [CRes]. The new type system is given by replacing, in Figure 6, rules [Acc], [Req], [Cat], [Conc], [CRes], and [Bot] by the rules below.

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \cdot x\colon \alpha}{\Theta;\Gamma, a\colon \langle \alpha, \overline{\alpha}\rangle \vdash \texttt{accept}\ a(x)\ \texttt{in}\ P \triangleright \Delta} \quad [\textsc{Acc}]$$

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \cdot x\colon \overline{\alpha}}{\Theta;\Gamma, a\colon \langle \alpha, \overline{\alpha}\rangle \vdash \texttt{request}\ a(x)\ \texttt{in}\ P \triangleright \Delta} \quad [\textsc{Req}]$$

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \cdot k\colon \beta \cdot x\colon \alpha}{\Theta;\Gamma \vdash \texttt{catch}\ k(x)\ \texttt{in}\ P \triangleright \Delta \cdot k\colon ?[\alpha];\beta} \quad [\textsc{Cat}]$$

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \qquad \Theta;\Gamma \vdash Q \triangleright \Delta'}{\Theta;\Gamma \vdash P \mid Q \triangleright \Delta \cdot \Delta'} \quad [\textsc{Conc}]$$

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \cdot \kappa^+\colon \alpha \cdot k^-\colon \overline{\alpha}}{\Theta;\Gamma \vdash (\nu\kappa)P \triangleright \Delta} \quad [\textsc{CRes}]$$

$$\frac{\Theta;\Gamma \vdash P \triangleright \Delta \qquad \kappa \text{ not in } \Delta}{\Theta;\Gamma \vdash (\nu\kappa)P \triangleright \Delta} \quad [\textsc{CRes'}]$$

3.3 Subject Reduction and Type Safety

The absence of typing compatibility (in rule [Par]) is compensated by balanced typings. We say that a typing Δ is *balanced* if whenever $\kappa^+\colon \alpha, \kappa^-\colon \beta \in \Delta$, then $\alpha = \overline{\beta}$. Subject-Reduction (Theorem 3.3) and Type Safety (Theorem 3.4) hold only in presence of balanced typings.

We rely on the Weakening, Strengthening, Channel and Substitution Lemmas of Section 2.4, adapted to the syntax and typing system of Section 2. Since we now replace channels in processes, we need a Channel Replacement Lemma, a result not needed for the ESOP'98 system [12].

Lemma 3.1 (Channel Replacement) $\Theta;\Gamma \vdash P \triangleright \Delta \cdot x\colon \alpha$ *implies* $\Theta;\Gamma \vdash P[\kappa^p/x] \triangleright \Delta \cdot \kappa^p\colon \alpha$.

Proof. A straightforward induction on the derivation tree for P. □

Lemma 3.2 (Subject Congruence) $\Theta;\Gamma \vdash P \triangleright \Delta$ *and* $P \equiv Q$ *imply* $\Theta;\Gamma \vdash Q \triangleright \Delta$.

Proof. The proof follows the pattern of that of Lemma 2.9. We detail the two most interesting cases.

Case $P \mid \texttt{inact} \equiv P$**.** We show that if $\Theta;\Gamma \vdash P \mid \texttt{inact} \triangleright \Delta$, then $\Theta;\Gamma \vdash P \triangleright \Delta$. Suppose that

$$\Theta;\Gamma \vdash P \triangleright \Delta_1 \quad \text{and} \quad \Theta;\Gamma \vdash \texttt{inact} \triangleright \Delta_2$$

with $\Delta_1 \cdot \Delta_2 = \Delta$. Note that Δ_2 only contains `end`. Applying Weakening to P, we have $\Theta; \Gamma \vdash P \triangleright \Delta_1 \cdot \Delta_2$ as required.
The other direction is similar.

Case $(\nu u)P \mid Q \equiv (\nu u)(P \mid Q)$ if $u \notin \mathrm{fu}(Q)$**.** The case when u is a name is standard. Suppose u is channel k and assume $\Theta; \Gamma \vdash (\nu\kappa)(P \mid Q) \triangleright \Delta$. We consider the [CRes] case (the [CRes'] case is simpler):

$$\frac{\Theta; \Gamma \vdash P \triangleright \Delta_1 \qquad \Theta; \Gamma \vdash Q \triangleright \Delta_2}{\Theta; \Gamma \vdash P \mid Q \triangleright \Delta \cdot \kappa^p \colon \alpha \cdot \kappa^{\overline{p}} \colon \overline{\alpha}}$$

First notice that κ^p and $\kappa^{\overline{p}}$ can be both in either Δ_i' or one in each. When they are both in Δ_1 we conclude the case by applying [CRes] and [Par]. When they are both in Δ_2, by the Channel Lemma we know that the types for κ^p and $\kappa^{\overline{p}}$ in Δ_2 are `end`. We conclude the case by applying Strengthening to Q before applying [CRes'] and [Par]. Finally, when κ^p is in Δ_1' and $\kappa^{\overline{p}}$ in Δ_2', we apply Strengthening to both P and Q before applying [CRes'] and [Par]. □

Theorem 3.3 (Subject Reduction) *$\Theta; \Gamma \vdash P \triangleright \Delta$ with Δ balanced and $P \to^* Q$ imply $\Theta; \Gamma \vdash Q \triangleright \Delta'$ and Δ' balanced.*

Proof. The proof is similar to that of Theorem 2.10. We concentrate on the four new reduction rules, and reuse the remaining cases.

Case [Link] $(\texttt{accept}\ a(x)\ \texttt{in}\ P_1) \mid (\texttt{request}\ a(x)\ \texttt{in}\ P_2) \to (\nu\kappa)(P_1[\kappa^+/x] \mid P_2[\kappa^-/x])$**.** The assumption is derived from

$$\frac{\Theta; \Gamma \vdash P_1 \triangleright \Delta \cdot x \colon \alpha}{\Theta; \Gamma, a \colon \langle \alpha, \overline{\alpha} \rangle \vdash \texttt{accept}\ a(x)\ \texttt{in}\ P_1 \triangleright \Delta}$$

from

$$\frac{\Theta; \Gamma \vdash P_2 \triangleright \Delta \cdot x \colon \overline{\alpha}}{\Theta; \Gamma, a \colon \langle \alpha, \overline{\alpha} \rangle \vdash \texttt{request}\ a(x)\ \texttt{in}\ P_2 \triangleright \Delta}$$

and from [Par] with $\Delta_1 \cdot \Delta_2 = \Delta$. Applying the Channel Replacement Lemma to P_1 and also to P_2, we have $\Theta; \Gamma \vdash P_1[\kappa^+/x] \triangleright \Delta \cdot \kappa^+ \colon \alpha$, and $\Theta; \Gamma \vdash P_2[\kappa^-/x] \triangleright \Delta \cdot \kappa^- \colon \overline{\alpha}$. The case concludes with the application of rule [Par] followed by rule [CRes].

Case [Com] $(\kappa^p![\tilde{e}]; P_1) \mid (\kappa^{\overline{p}}?(\tilde{x})\ \texttt{in}\ P_2) \to P_1 \mid P_2[\tilde{c}/\tilde{x}]$**.** The assumption is derived from:

$$\frac{\Gamma \vdash \tilde{e} \triangleright \tilde{S} \qquad \Theta; \Gamma \vdash P \triangleright \Delta_1 \cdot \kappa^p \colon \alpha}{\Theta; \Gamma \vdash k![\tilde{e}]; P_1 \triangleright \Delta_1 \cdot \kappa^p \colon ![\tilde{S}]; \alpha} \qquad \frac{\Theta; \Gamma \cdot \tilde{x} \colon \tilde{S} \vdash P_2 \triangleright \Delta_2 \cdot \kappa^{\overline{p}} \colon \overline{\alpha}}{\Theta; \Gamma \vdash k?(\tilde{x})\ \texttt{in}\ P_2 \triangleright \Delta_2 \cdot \kappa^{\overline{p}} \colon ?[\tilde{S}]; \overline{\alpha}}$$

and [Par] with $\Delta_1 \cdot \kappa^p \colon ![\tilde{S}]; \alpha \cdot \Delta_2 \cdot \kappa^{\overline{p}} \colon ?[\tilde{S}]; \overline{\alpha} = \Delta$. Notice that the types for κ^p and for $\kappa^{\overline{p}}$ are dual since Δ is balanced by hypothesis. Then by (3), page 10, we know $\Gamma \vdash \tilde{c} \triangleright \tilde{S}$. We conclude the case by applying Substitution Lemma to P_2, and the [Par]-rule to P_1 and to $P_2[\tilde{c}/\tilde{x}]$.

Case [Label]**.** Similar to the homonymous case in the proof of Theorem 2.10, relying, as above, on the fact that Δ is balanced.

Case [Pass] $(\texttt{throw}\ \kappa^p[\kappa'^q]; P_1) \mid (\texttt{catch}\ \kappa^{\overline{p}}(x)\ \texttt{in}\ P_2) \to P_1 \mid P_2[\kappa'^q/x]$**.** The assumption is derived from

$$\frac{\Theta; \Gamma \vdash P_1 \triangleright \Delta_1 \cdot \kappa^p \colon \beta}{\Theta; \Gamma \vdash \texttt{throw}\ \kappa^p[\kappa'^q]; P_1 \triangleright \Delta_1 \cdot \kappa^p \colon ![\alpha]; \beta \cdot \kappa'^q \colon \alpha}$$

from

$$\frac{\Theta;\Gamma \vdash P_2 \triangleright \Delta_2 \cdot \kappa^{\overline{p}} : \overline{\beta} \cdot x : \alpha}{\Theta;\Gamma \vdash \texttt{catch}\ \kappa^{\overline{p}}(x)\ \texttt{in}\ P_2 \triangleright \Delta_2 \cdot \kappa^{\overline{p}} : ?[\alpha];\overline{\beta}}$$

and from [Par] with $\Delta_1 \cdot \kappa^p : ![\alpha];\beta \cdot \kappa'^q : \alpha \cdot \Delta_2 \cdot \kappa^{\overline{p}} : ?[\alpha];\overline{\beta} = \Delta$. Once again, the types for κ^p and for $\kappa^{\overline{p}}$ are dual since Δ is balanced by hypothesis. Applying the Channel Replacement Lemma to P_2, we obtain

$$\Theta;\Gamma \vdash P_2[\kappa'^q/x] \triangleright \Delta_2 \cdot \kappa^{\overline{p}} : \overline{\beta} \cdot \kappa'^q : \alpha$$

By applying [Par] to P_1 and $P_2[\kappa'^q/x]$, we obtain the required result. □

Theorem 3.4 (Type Safety) *A program typable under a balanced channel environment never reduces into an error.*

Proof. The proof follows the pattern of that of Theorem 2.11, only that the contradiction happens not because typing composition ($\Delta \circ \Delta'$) is not defined, but because the resulting typing ($\Delta \cdot \Delta'$) is not balanced. □

4 Conclusion

The study of session typing system is now widespread due to the need for structured communications in various scenarios in distributed applications. They have been studied, at the research levels, for the π-calculus [3, 10, 11, 12, 13, 17, 20], Ambients [5], CORBA interfaces [18], multi-threaded functional languages [21], Web Description Languages [4], and distributed [7] and multi-threaded Java [6] and, at the industry level, WC3-CDL [22] and pi4Tech [16].

In the presence of higher-order session communication, session instantiation dynamically changes structures of sessions during execution, so that it becomes non-trivial to preserve typability. Unfortunately the authors of the previous session typing systems did not realise (or even *forgot* about) the key point of rule [Pass], so that some of the session typing systems published after [12, 17] fail to satisfy the Subject Reduction Theorem. As discussed in this report, the subtlety of the type preservation is related to a treatment of communication channels in the operational semantics of the π-calculus: aliasing of channels, structured safe communications, types, new name creations and the α-conversions are tightly related with this issue.

As a future work, it would be nice to investigate the relationship uniformly using some Rewriting framework [8, 9].

References

[1] H.P. Barendregt. *The Lambda Calculus: Its Syntax and Semantics*. North-Holland, Amsterdam, 1984.

[2] Eduardo Bonelli, Adriana Compagnoni, and Elsa Gunter. Private communication, 2003.

[3] Eduardo Bonelli, Adriana Compagnoni, and Elsa Gunter. Correspondence Assertions for Process Synchronization in Concurrent Communications. *Journal of Functional Programming*, 15(2):219–248, 2005.

[4] Marco Carbone, Kohei Honda, and Nobuko Yoshida. A Theoretical Basis of Communication-centered Concurrent Programming. Web Services Choreography Working Group mailing list, to appear as a WS-CDL working report.

[5] Adriana Compagnoni, Mariangiola Dezani-Ciancaglini, and Pablo Garralda. BASS:Boxed Ambients with Safe Sessions. In *Proceedings of PPDP'06*. ACM Press, 2006.

[6] Mariangiola Dezani-Ciancaglini, Dimitris Mostrous, Nobuko Yoshida, and Sophia Drossopoulou. Session types for object-oriented languages. In *The 20th European Conference on Object-Oriented Programming*, LNCS. Springer-Verlag, 2006.

[7] Mariangiola Dezani-Ciancaglini, Nobuko Yoshida, Alexander Ahern, and Sophia Drossopoulou. A distributed object-oriented language with session types. In *Symposium on Trustworthy Global Computing*, LNCS. Springer-Verlag, 2005.

[8] Maribel Fernández and Murdoch J. Gabbay. Nominal rewriting with name generation: abstraction vs. locality. In *Proc. 7th ACM-SIGPLAN Symposium on Principles and Practice of Declarative Programming (PPDP'05)*. ACM Press, 2005.

[9] Maribel Fernández, Murdoch J. Gabbay, and Ian Mackie. Nominal rewriting systems. In *Proc. 6th ACM-SIGPLAN Symposium on Principles and Practice of Declarative Programming (PPDP'04)*. ACM Press, 2004.

[10] Simon J. Gay and Malcolm J. Hole. Types and subtypes for client-server interactions. In *ESOP'99*, LNCS, pages 74–90. Springer-Verlag, 1999.

[11] Simon J. Gay and Malcolm J. Hole. Subtyping for session types in the pi calculus. *Acta Informatica*, 42(2–3):191–225, 2005.

[12] Kohei Honda, Vasco T. Vasconcelos, and Makoto Kubo. Language primitives and type disciplines for structured communication-based programming. In *ESOP'98*, volume 1381 of *LNCS*, pages 22–138. Springer-Verlag, 1998.

[13] Karol Ostrovský. *On modelling and analysing concurrent systems*. PhD thesis, Chalmers University of Technology, 2006.

[14] Benjamin C. Pierce. *Types and Programming Languages*. MIT Press, 2002.

[15] Davide Sangiorgi. π-calculus, internal mobility and agent-passing calculi. *Theoretical Computer Science*, 167(2):235–274, 1996.

[16] Conversation with Steve Ross-Talbot. *ACM Queue*, 4(2), March 2006.

[17] Kaku Takeuchi, Kohei Honda, and Makoto Kubo. An Interaction-based Language and its Typing System. In *PARLE'94*, volume 817 of *LNCS*, pages 398–413. Springer-Verlag, 1994.

[18] Antonio Vallecillo, Vasco T. Vasconcelos, and António Ravara. Typing the Behavior of Objects and Components using Session Types. In *FOCLASA'02*, volume 68(3) of *ENTCS*. Elsevier, 2002.

[19] Vasco T. Vasconcelos. Recursive types in a calculus of objects. *Transactions of Information Processing Society of Japan*, 35(9):1828–1836, September 1994.

[20] Vasco T. Vasconcelos, Simon Gay, and António Ravara. Typechecking a multithreaded functional language with session types. *Theoretical Computer Science*, 2006. To appear.

[21] Vasco T. Vasconcelos, António Ravara, and Simon Gay. Session Types for Functional Multithreading. In *CONCUR'04*, volume 3170 of *LNCS*, pages 497–511. Springer-Verlag, 2004.

[22] Web Services Choreography Working Group. Web Services Choreography Description Language. http://www.w3.org/2002/ws/chor/.